

Calibrating models of ultralow-mass stars

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Abstract. Evolutionary and atmospheric models have become available for young ultralow-mass objects. These models are being used to determine fundamental parameters from observational properties. TiO bands are used to determine effective temperatures in ultralow-mass objects, and together with Na- and K-lines to derive gravities at the substellar boundary. Unfortunately, model calibrations in (young) ultralow-mass objects are rare. As a first step towards a calibration of synthetic spectral features, I show molecular bands of TiO, which is a main opacity source in late M-dwarfs. The TiO ϵ -band at 8450 Å is systematically too weak. This implies that temperatures determined from that band are underestimated, and I discuss implications for determining fundamental parameters from high resolution spectra.

Key words: Stars – low-mass, brown dwarfs; Stars – atmospheres; Line – profiles

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1. Introduction

The amount of observational data on young very low mass objects is growing rapidly. The classification into spectral types according to major absorption features, and a comparison to spectral energy distributions can provide a temperature scale that extends down to the coolest known objects and connects to stars of spectral type M and hotter (Golimowski et al., 2004). However, fundamental parameters for ultralow-mass objects, particularly for very young objects, are only poorly known and theory is not yet able to reliably predict such parameters. A number of discoveries have casted doubt on the applicability of evolutionary tracks at young ages and low masses (e.g., Hillenbrand & White 2004; Close et al. 2005, Reiners et al. 2005) – a non surprising fact since the models are not expected to hold at such young ages anyway.

Tests of evolutionary models come from systems where preferably mass and age are known, i.e. predominantly from binaries in clusters or star forming regions. Masses of binaries can be measured directly and provide the most reliable test of theory. A second way to obtain fundamental parameters without using evolutionary models is to derive them from comparison to synthetic spectra. In high resolution spectra ($R \gtrsim 20\,000$), a number of sensitive tracers can be found which are sensitive to temperature and gravity. Mohanty et

al. (2004a, 2004b) have recently derived the fundamental parameters temperature, gravity, radius and mass from high resolution spectra for a number of members of the UpSco association (5 Myr). They compared their results to evolutionary tracks from Baraffe et al. (1998) and Chabrier, Baraffe & Hauschildt (2000), and found significant disagreement between their observations and evolutionary models.

Stellar parameters derived from comparison to synthetic spectra are independent of evolutionary models, but completely depend on the spectral synthesis involving atmospheric (temperature) structure and molecular data. In the following, currently available synthetic high resolution spectra generated with the PHOENIX code shall be compared to spectra of stars with known atmospheric parameters T_{eff} , $\log g$ and metallicity. I will show that some tracers of the current models do not yield correct temperatures and I will discuss the implications for derived temperatures and gravities.

2. Temperature and gravity from high resolution spectra

A number of spectroscopic absorption features are very sensitive to temperature and gravity. While temperature can also be derived from low resolution spectra by investigating spectral energy distributions, high spectral resolution is required to obtain the surface gravity (low resolution spectra are only sensitive to about one dex in $\log g$).

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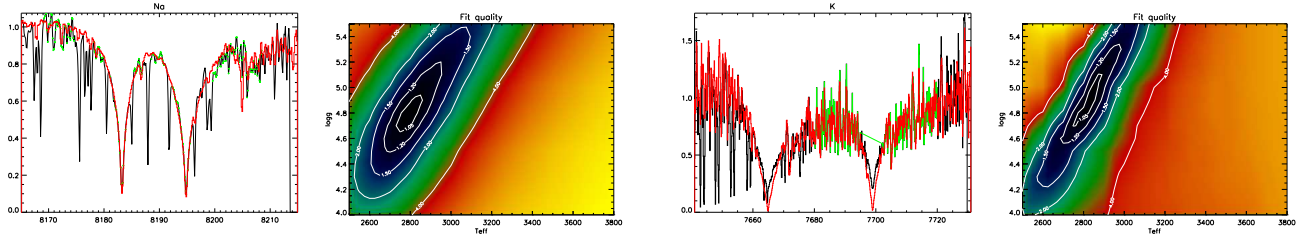


Fig. 1. Fits of synthetic spectra to Na (left two panels) and K (right two panels) resonance doublets of G1406. For each case the spectral region is shown (black line: data; green symbols: data points used for fit; red line: fit). Right to the spectral region the fit quality is shown as a contour plot in T_{eff} and $\log g$, darker color means better fit. Both regions are sensitive to T_{eff} and $\log g$ and yield consistent results.

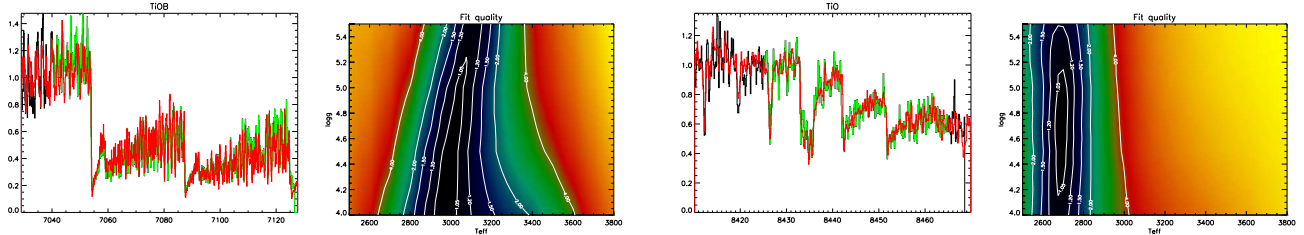


Fig. 2. As Fig. 1 but for the two TiO bands; γ -band left, ϵ -band right. Although good fit quality is achieved in both regions, the temperatures derived are inconsistent. Note that TiO does only marginally depend on gravity.

In Fig. 1 the two gravity sensitive resonance doublets of Na and K from a spectrum of G1406 (CN Leo, M5.5V) are shown. For each doublet the lines are shown with a model fit overplotted (see caption). Next to the spectra, the fit quality is displayed in a contour plot as a function of T_{eff} and $\log g$, darker color implying a better fit. As can be seen in both contour plots, the lines are extremely sensitive to temperature and gravity, but the best fit is degenerate in T_{eff} and $\log g$. Thus, it is possible to determine a range in T_{eff} and $\log g$ from Na and K lines in high resolution spectra. However, to pin down a single solution in temperature and gravity, it is necessary to obtain at least one independent measurement in a region that shows a different temperature/gravity dependence.

Such an independent measurement can be provided by molecular absorption bands of TiO which are extremely sensitive to temperature, but are virtually insensitive to gravity. Spectral regions with fits to the same data as above and fit quality contour plots are shown in Fig. 2 for two different bands of TiO (γ -band left, ϵ -band right).

The strategy is to derive the temperature from the TiO bands, and to determine the surface gravity from Na/K with the temperature known from TiO. However, as can be seen in Fig. 2, the two TiO regions do not provide consistent temperatures. This does not only rise the question which of the bands is more reliable, it implies that some fundamental problem exists in the synthetic spectra of relatively hot objects (note that at spectral type M5.5 dust formation is not a problem). None of the temperatures derived from TiO should be trusted without further investigation.

Table 1. Calibrator stars for which temperature and gravity are known from interferometric radius measurements

Object	Sp	T_{eff} [K]	$\log g$	[Fe/H]
GJ 191	M1V	3570 ± 156^a	4.96 ± 0.13^a	-0.86^c
GJ 205	M1.5V	3520 ± 170^a	4.54 ± 0.06^a	-0.45^d
GJ 411	M2V	3570 ± 42^a	4.85 ± 0.03^b	-0.4^c
GJ 699	M4V	3134 ± 102^b	5.04 ± 0.10^b	-0.75^c
GJ 551	M5.5V	3042 ± 117^a	5.20 ± 0.23^a	≥ 0.0

^a Ségransan et al. (2003)

^b Dawson & Robertis (2004)

^c Woolf & Wallerstein (2005)

^d Woolf & Wallerstein (2005) report [Fe/H] = 0.21 for $T_{\text{eff}} = 3760$ K; using T_{eff} and $\log g$ from Ségransan et al. (2003) yields the same TiO band strengths with [Fe/H] = -0.45

3. Comparison to stars with known parameters

To investigate the inconsistency of the model spectra, they can be compared to spectra from stars with known temperature and gravity. The probably most reliable values of T_{eff} and $\log g$ come from interferometric radius measurements which have been performed in some M-dwarfs by Ségransan et al. (2003) and Dawson & Robertis (2004). Metallicities are available for some of them from a careful investigation by Woolf & Wallerstein (2005). Low mass stars with measured radii and available high resolution spectra are listed in Table 1. For Proxima Cen a number of studies indicate that its companions are at least of solar metallicity, and I use [Fe/H] = 0 yielding very good agreement in the γ -band.

The two TiO-bands of these stars are shown as colored lines in Fig. 3. Synthetic spectra according to their tem-

perature and surface gravity are overplotted as grey lines. The γ -band appears stronger than the ϵ -band; while the former is visible in all targets, the latter is not detected in the two hottest objects. GJ 191 and GJ 205 consequently are not shown in the right panel of Fig. 3.

In all five calibrator stars, the model spectra provide an excellent fit in the region of the γ -band (left panel of Fig. 3). The model sequence reproduces the correct absorption strength and its growth with decreasing effective temperature. On the other hand, the ϵ -band in the right panel of Fig. 3 does not fit the observations but systematically underestimates the absorption strength in all three spectra investigated. Thus, the temperature derived from the γ -band can be expected to be very accurate, while the temperature obtained from comparison to the ϵ -system may be systematically too low, since lowering the temperature would also enhance the (underestimated) band strength and provide a better fit.

In Fig. 4, the ϵ -band spectra are shown as in the right panel of Fig. 3, but now the absorption strength has been artificially enhanced by 70% by simply shifting the zero point (note that this also amplifies the atomic Ti lines at for example 8435 Å, only the smooth features redward of 8440 Å are due to TiO). These modified models now provide excellent fits in all three stars. Together with the accurate consistency achieved in the γ -band, this suggests that the ϵ -band is systematically underestimated in the models.

From this first estimate, it can be speculated what could be the reason for the underestimated band strength in the ϵ -system. One reason can be that the current treatment of the partition function of TiO is inappropriate (Allard, these proceedings). However, a fundamental change of the TiO abundance probably would influence the γ -band as well, but this one is in nice agreement with the observations. A parameter that influences the ϵ -band strength only is the oscillator strength f_{el} . As a first order approximation, an oscillator strength 70% higher than the one used for the calculations would provide a TiO absorption strength that is enhanced by roughly 70% (the ϵ system is not saturated in this regime). Oscillator strengths for TiO from different ab initio calculations and laboratory experiments together with the values adopted for the currently available PHOENIX models are given in Allard, Hauschildt & Schwenke (2000). Their Table 1 shows that for the ϵ -band f_{el} is not very well confined and a slightly higher value would be in agreement with laboratory experiments and calculations as well.

Of course, a different oscillator strength of the main opacity source in very cool stars would have much more influence to the atmospheric structure than just an enhancement of the absorption strength in one molecular band. Thus, the suggested enhancement of $f_{\text{el}}(\epsilon)$ of 70% can only be a first order guess that has to be confirmed by self-consistently calculated atmospheres (and with the correct treatment of the partition function).

4. Implications for fundamental parameters

Temperatures derived from model fits to the TiO ϵ -band have been used for example by Mohanty et al. (2004a, 2004b) to

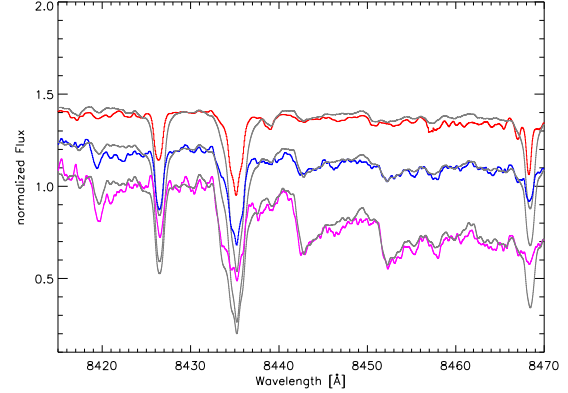


Fig. 4. As right panel in Fig. 3, but with absorption features artificially enhanced by 70%. The enhanced TiO band fits the data in all three cases.

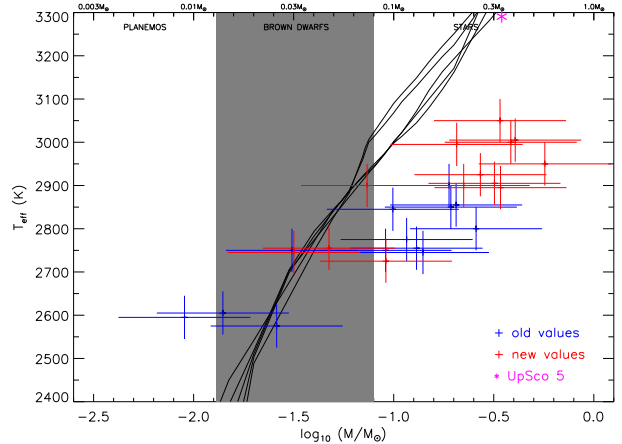


Fig. 5. Temperature and mass for the members of the young association UpSco (Mohanty et al. 2004b). Blue crosses show parameters derived from the original models, red crosses are derived using the adjusted TiO bands (see text).

derive fundamental parameters of young low mass objects. A reinvestigation of T_{eff} from the modified ϵ -band, which has been artificially enhanced by 70%, yields temperatures about 150–200 K higher than what was derived from the original models. Since determinations of surface gravity in high resolution spectra employ the effective temperature from TiO to dissolve the degeneracy in T_{eff} and $\log g$ (Sect. 2), surface gravities are also effected. A comparison to Fig. 1 shows that a temperature change of ≈ 200 K shifts the gravity to values higher by roughly 0.3 dex at 2700 K (the correction does depend on temperature and has to be individually calculated for each star). Radii as well as masses consequently are also effected by a temperature shift (cp. Basri, these proceedings).

In Fig. 5, temperatures and masses of the sample targets from Mohanty et al. (2004a, 2004b) are plotted (cp. Fig. 3 in Mohanty et al. 2004b). The original values are shown in blue, red symbols display the new values according to a shift of 150 K and the corresponding gravity shift. Note that these new values are only estimates from the qualitative changes discussed above, no proper reanalysis has been done; Fig. 5

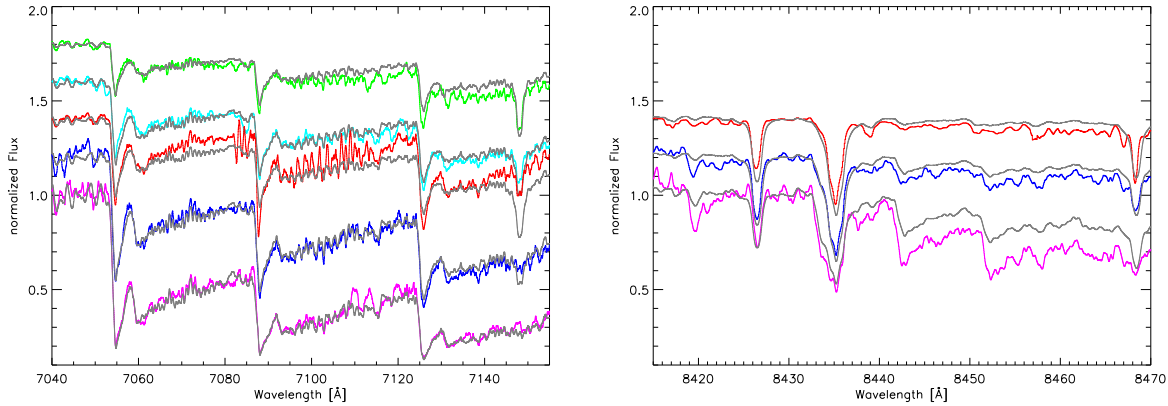


Fig. 3. Spectra of stars with known T_{eff} and $\log g$, overplotted are models according to temperature and gravity. Left: γ -band; right: ϵ -band. In the left panel from top to bottom: GJ 191, GJ 205, GJ 411, GJ 699 and GJ 551. In the right panel only the three coolest stars are shown, the hotter two show no absorption in this region. Different spectra are plotted with an offset of 0.2.

only displays the approximate trends. Nevertheless, the discrepancy between the data points and evolutionary tracks (shown as solid lines in Fig. 5) vanishes at very low masses. In fact, the lowest mass objects are shifted into the brown dwarf mass regime. On the other hand, the discrepancy becomes even larger for the hottest objects, unphysically high masses of about one third of a solar mass are estimated for objects of spectral type around M6 (cp. Mohanty et al. 2004b for details on the sample targets). The recently discovered spectroscopic binary UpScoCTIO 5 (Reiners et al. 2005) is also plotted in Fig. 5. Although UpScoCTIO 5 shows a significant discrepancy to the evolutionary models (which is hardly visible in this figure), its dynamical mass of $M \geq 0.32 M_{\odot}$ at a spectral type M4 is already lower than what is derived for M6 objects using the high resolution fits. This clearly shows that the far stronger disagreement between evolutionary models and the corrected values in Fig. 5 must be due to incorrect masses derived from the synthetic spectra.

5. Summary

Synthetic PHOENIX spectra have been compared to high resolution spectra of stars with known atmospheric parameters. Absorption bands of TiO are sensitive to temperature but insensitive to gravity. The resonance doublets of Na and K are sensitive to both, T_{eff} and $\log g$. Temperatures derived from the two TiO bands, which belong to the γ and ϵ system, differ by 150–200 K. The γ -band yields temperatures consistent with the known parameters, ϵ -band temperatures are systematically too low. Enhancing the ϵ -band by 70% makes this band fit to the spectra. It is suggested that the oscillator strength employed for the ϵ -band is too low by about 70%.

For the sample investigated by Mohanty et al. (2004a, 2004b), new temperatures are estimated from modified models with artificially enhanced band strengths, and the according gravities are estimated from Na and K employing the corrected temperatures. The derived masses are obviously too high suggesting a problem in the Na and K resonance lines that are used to derive gravity and thus mass.

What can be the reason for the incorrect Na and K lines? The Na lines are embedded in the TiO- ϵ system which is probably too weak as shown above. Stronger TiO absorption will effect the Na lines but is not expected to have much influence on the K line. It is important to note that both doublets show the same (wrong) behaviour, which makes it probable that only one mechanism is responsible for the wrong line shape in both systems. Burrows & Volobuyev (2003) and Allard et al. (2003) present an improved model on line shape theory for the Na and K resonance lines. Their improvements have not yet been incorporated into the PHOENIX models and should be implemented soon (Allard, these proceedings).

These major improvements, namely more accurate ϵ -band oscillator strengths and improved Na and K line shape theory, are the most promising candidates to provide better Na and K lines and to yield correct temperatures, gravities, and hence masses. As soon as new models are available, it is necessary to compare the new Na and K lines to the stellar spectra as done here. Such a comparison is an essential first step in order to correctly interpret any inconsistencies – and also the agreements – between observations and evolutionary models.

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